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A FORTHCOMING KEY PRESS CAN BE SELECTED WHILE EARLIER ONES ARE EXECUTED

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CONTENTS | Page

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SUMMARY

This paper addresses the issue of selecting a response while executing earlier response movements. Although there is the general notion that this may be possible there is no conclusive evidence on whether it can occur without interference. A direct test of whether concurrent response selection of a present and execution of previous responses develops with practice was carried out by having subjects press a number of keys, determined in advance, prior to pressing a stimulus-dependent key. Response selection demands were varied by utilizing spatially compatible and incompatible stimulus-response mappings the demands of which are known not to diminish much with practice. The results show that the longer time needed to select an incompatible response vanishes almost entirely when the stimulus-dependent response is preceded by two or four predetermined key presses. The conclusion is drawn that response selection can concur with the execution of movement sequences without interference.

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Soesterberg

Een toetsdruk kan geselecteerd worden gedurende uitvoering van eerdere toetsdrukken

W.B. Verwey

SAMENVATTING

In dit rapport wordt de mogelijkheid onderzocht responsen te selecteren terwijl eerdere responsen worden uitgevoerd. Hoewel wel het idee bestaat dat dit mogelijk moet zijn, zijn er geen data die aantonen dat het kan zonder interferentie. Dit werd op directe wijze onderzocht door proefpersonen eerst een aantal toetsen in te laten drukken die van tevoren bekend waren en daarna een toets die bepaald werd door de aangeboden stimulus. De moeilijkheid van de toets-selectie werd gevarieerd door incompatibele en compatibele stimulus-response mappings te gebruiken. Van stimulus-response compatibiliteit is bekend dat het alleen het response-selectie proces beïnvloedt en dat het effect ervan weinig verandert met oefening. De resultaten laten zien dat het compatibiliteitseffect praktisch geheel verdwijnt indien een keuze-toets voorafgegaan wordt door twee of vier bekende toetsen. De conclusie wordt getrokken dat response selectie kan plaatsvinden tijdens uitvoering van eerdere bewegingen zonder dat er interferentie optreedt.

1 INTRODUCTION

A main issue in research on human skills and human skill acquisition concerns the extent processing and action may concur in relation to the amount of practice (Portier & Van Galen, in press; Salthouse, 1986; Semjen, 1992; Verwey, in press). The assumption of concurrent processing has been put forward for various sequential tasks such as typing (Salthouse, 1986), writing (Van Galen et al., 1986), sequential key pressing (Semjen, 1992), and musical performance (Shaffer, 1976). One general idea is that movement sequences are made up of a flexible concatenation of fairly rigid motor chunks (Jordan, 1990; Keele et al., 1990). Concurrent selection of forthcoming chunks during execution of earlier chunks would then allow fast and still flexible production of long movement sequences. But it is not clear which processes can actually concur without interference and, if interference occurs, in what phase of execution this will be. Multiple resource theories (Sanders, 1983; Wickens, 1984) suggest that response selection and motor execution may be processing stages that can easily concur but recent results (Verwey, in press) suggested otherwise. The major objective of this paper is to test concurrence of these stages.

In one experimental paradigm subjects carry out a sequence of responses to a stimulus, the elements of which are either fully fixed (stimulus-independent) or all fixed with the exception of one - usually the final one - which is stimulus-dependent. The question is, then, whether the stimulus-dependent response can be selected while the earlier responses are carried out, which implies that neither the time for initiating the sequence nor the speed of executing the fixed responses should be affected by the stimulus-dependent response. Verwey (in press) investigated this question in a sequential one-finger key pressing task; he found that the time required for initiating a fully fixed sequence of three key presses was less than the time needed to initiate a sequence in which the final (third) key press was stimulus-dependent. This result did not notably change after prolonged practice, which led to the conclusion that selection of a response can not occur while executing the earlier fixed part of the response sequence, even after prolonged practice.

Verwey's results are at odds, however, with other evidence suggesting that concurrent response selection does not affect movement execution and can easily concur. For example, Garcia-Colera and Semjen (1988) showed that the effect of an accentuated tap in a sequence of three to eight repetitive key presses decreased as an inverse function of the time-distance between the initial tap and the first point at which the accentuated tap occurred. It was concluded that execution of the initial, predictable sequence part started before the variable part was "planned". The observation that interkey intervals did not increase suggested concurrent processing without interference. In another sequential key pressing study, in which each of four fingers pressed a different key at the highest rate possible, the effect of a stimulus-dependent key press on sequence initiation time was also found to be less as the position of the stimulus-

dependent key press was later in the sequence (Rosenbaum et al., 1987). Yet, these studies do not unambiguously show that there was no interference between selection and execution. In the tapping task of Garcia-Colera and Semjen (1988) tapping was not at the highest rate possible and, hence, interference between selection and execution may have been absent because subjects might have processed during interkey pauses. In the Rosenbaum et al. (1987) study the smaller effect on initiation time as the choice response was later in the sequence, was accompanied by longer interkey intervals. According to Rosenbaum et al. (1987) this was caused by the need for traversing more nodes in a tree-traversal process during sequence execution (cf. Rosenbaum et al., 1983). However, one can not exclude that the interkey times were lengthened by concurrent selection of the stimulus-dependent key press.

On the other hand, Verwey's data might also not allow the general conclusion that selection and execution cannot concur. Thus, his three key press sequences might have been too short to permit concurrence to develop. Also, Rosenbaum et al. (1987) and Garcia-Colera and Semjen (1988) had repeated tapping of one or two keys prior to the stimulus-dependent response while Verwey (in press) used a more complex fixed sequence. The complexity of the fixed sequence might well affect the extent of concurrent response selection. Finally, the fixed vs. stimulus-dependent sequences in Verwey's study differed in the number of stimulus alternatives - i.e. four stimuli occurred in the stimulus-dependent and one in the fixed condition. Stimulus probability is known to not only affect response selection but perceptual processing stages as well (Sanders, 1980, 1990). Hence, the consistent effect of stimulus-dependence on initiating the sequence might have been due to perceptual processing rather than to response selection.

Thus, the issue of concurrent response selection and movement execution appears still largely unsettled. This paper aims at contributing to the research by studying (a) the effect of the length of the fixed sequence and (b) the effects of response selection separately from perceptual processing. In order to trace the moment that the choice response was selected, the selection demands were manipulated by using spatially compatible and incompatible stimulus-response (S-R) mappings. S-R compatibility is particularly suitable to investigate this issue because its effects are limited to response selection (Sanders, 1990) and because the size of the effect is fairly resistent to practice (Fitts & Seeger, 1953; Dutta & Proctor, 1992). When the stimulus-dependent key would be selected before the sequence is initiated, the effect of S-R compatibility should be in the initiation latency. This is actually similar to the Inhoff et al. (1984) prediction for a multi-finger key pressing sequence. If, however, response selection concurs with sequence execution, initiation time should not exhibit the compatibility effect. It is of significant interest to check whether a lack of compatibility effect on initiation time would go together with an effect on interkey intervals. Since there might be more opportunity for concurrent response selection with longer sequences it was anticipated that concurrent response selection would develop easier in longer than in shorter sequences. The time that keys were actually

depressed and the time to move from one key to the next were registered separately in order to find out whether depression times would perhaps reflect cognitively loading processes and, hence, would be more sensitive to concurrent tasks than movements of a more ballistic nature.

2 METHOD

2.1 Tasks

A trial started with a written instruction on a screen to press the "home key", i.e. the "5" key in the center of the keypad on a regular PC keyboard (Fig. 1). Pressing the "5" replaced the instruction by a plus-sign ('+') at the center of a square (1.3 × 1.4 cm) located in the middle of the screen. The plus functioned as fixation point and the combination of plus and square started a non-aging foreperiod which was always stopped after 4 s and which had the effect that subjects could not anticipate the moment of stimulus arrival (see Gottsdanker et al., 1986 for an elaborate discussion). At the end of the foreperiod the square was positioned with its midpoint either 6 cm to the left or to the right of the fixation point ('+'), which subtended a visual angle of about 5°. The square disappeared from the screen as soon as the home key was released. Subjects responded to the repositioning of the square with a sequence of either one, three, or five key presses, depending on the condition.

7	8	9
4	5	6
1	2	3

Fig. 1 Spatial lay-out of the keypad used for the key pressing sequences.

In the "one-key condition" the response consisted of releasing the home-key and pressing either the [4] or the [6] key. The response in the "three-key condition" consisted of pressing either [8 5 4] or [8 5 6] in about half of the blocks and pressing [2 5 4] or [2 5 6] in the other half. Which of these two sequence pairs was produced was determined randomly in advance of each trial block. Likewise, the "five-key condition" consisted of [8 5 2 5 4] and [8 5 2 5 6] on about half of the blocks and of [2 5 8 5 4] and [2 5 8 5 6] on the remaining blocks which was

also randomly determined in advance of each block. Thus, only the last key in the three- and five-key conditions was stimulus-dependent. The keys were pressed in rapid succession after releasing the home-key with the right index finger.

Stimulus-response mapping was varied between conditions. In the compatible condition a square shifting to the right required pressing the key located right from the home-key, i.e. the [6] key, and a square shifting to the left required depression of the key located left from the home-key, i.e. the [4] key. In the incompatible condition this mapping was reversed. The sequence length condition determined whether the choice key was pressed immediately or only after pressing earlier keys.

2.2 **Analyses and design**

There were three sets of time data. First, T_1 indicated the time between stimulus presentation and onset of the first key press and T_2, T_3, T_4, and T_5 indicated the interkey interval times. For example, T_2 indicated the time between onset of the first and the second key press. The second set of time data involved the time a particular key was pressed. Pressing time was the time between on- and offset of a key press and was indicated by T_{p1} through T_{p5}. For instance, T_{p1} indicated the interval between stimulus onset and releasing the home-key and T_{p2} the period that the first key was depressed. Finally, movement time T_{m1} through T_{m5} indicated the time between releasing a key and pressing the next key. So, for each of the T_x's ($1 \leq x \leq 5$) the following equation holds: $T_x = T_{px} + T_{mx}$. In addition, the number of errors was analyzed.

Subjects performed 15 experimental sessions, 7 sessions on day 1 and 8 sessions on day 2. Each session included two blocks. A block consisted of 74 trials, the first four of which were considered practice and excluded from analyses. S-R compatibility was varied within subjects in that half of the subjects first performed a compatible and then an incompatible block in each session and the other half first an incompatible and then a compatible block. In each of these groups, half of the subjects was randomly assigned to the three-key condition, the other half to the five-key condition. Hence, compatibility was a between-subjects variable. All subjects had one-key response blocks in session 2, 6, 9 and 13. Together, this resulted in a mixed 2 × 2 × 11 (compatibility × sequence length × session) design for the basic analysis of data obtained in the multi-key conditions and a 2 × 2 × 4 (compatibility × sequence length group × session) design for data obtained in the one-key condition (sequence length group was included here to check for differences between three- and five-key subjects). A 2 × 2 × 2 × 4 (one- vs. multi-key condition × sequence length × compatibility × session) design, involving the four one-key sessions and the three- and five-key sessions immediately preceding the one-key sessions, was used to test whether the compatibility effect differed in one- and multi-key conditions.

2.3 Subjects

In total, 26 right-handed students (20 females and 6 males) of Utrecht University participated as subjects. They all received Dfl. 90 for their participation. A bonus of Dfl. 20 was given to the three subjects in the three- and in the five-key group with fewest errors while still responding fast.

Four subjects were removed from the analyses. One because her finger nails obstructed key pressing, one because he had participated in an earlier study and was already highly experienced, and two because they had high average error percentages (16 and 23%). Twenty-two subjects remained, eleven in each sequence length group.

2.4 Procedure

Thirteen subjects visited the Institute at two consecutive mornings and thirteen at two consecutive afternoons. On the first day, a written instruction was handed out which briefly introduced the tasks and explained the way the computer had to be controlled. Then, after some additional oral instructions subjects were familiarized in a training session consisting of four 15-trial blocks. The first two blocks included a compatible and an incompatible one-key condition, the third and fourth block consisted of compatible and incompatible three- or five-key response conditions depending on the subjects' assignment to sequence length. Next, they performed seven experimental sessions including two one-key sessions. At day two the subjects performed the ensuing eight sessions, two of which included the one-key condition.

Both the morning and the afternoon subjects were split into two groups of six or seven subjects with three or four subjects from each length condition. These two groups worked in alternation: when one group was working, the other group relaxed in a separate room. This resulted in a 15 minutes work and rest schedule for each subject.

Each block of trials started with a written instruction about which stimuli could be expected and which keys had to be pressed. A sequence of key presses in one trial was considered wrong when an incorrect key was pressed or when the order was incorrect. In addition, the sequence was considered erroneous when pressing a key (i.e. T_x) took more than 1500 ms. In case of an error, subjects were informed immediately after the trial about the kind of error they had made. Inter-trial times were about 1600 ms, the first 1000 of which were reserved for presentation of error messages.

Following a block of 74 trials performance feedback was displayed in terms of the average time between stimulus onset and the moment of pressing the last key divided by the number of keys in the sequence and in terms of the error

proportion. An additional message stated that the subject had been too slow when, in the experimental sessions, the average time to release subsequent keys exceeded 350 ms. When more than 5 errors (i.e. more than 8 %) occurred at a particular block subjects were informed that they had made too many errors. There was a 23 s interval between the two blocks in each session.

2.5 Apparatus

The experiment was conducted on identical IBM AT compatible (386) computers with NEC multisync color monitors. Stimulus presentation and response collection were controlled through Micro Experimental Laboratory software (MEL - Schneider, 1988). Warning stimuli were presented at the center of the screen. At a typical viewing distance of about 65 cm the square subtended a visual angle of approximately 1°. The stimuli were presented in bright white on a black background and were viewed under normal room illumination. The response keys were part of the keypad of a normal AT-like keyboard. The distance between successive keys in a sequence was always 2.0 cm.

Six or seven subjects were simultaneously tested in separate sound-attenuated 2.4 × 2.5 × 2 m rooms. Each subject sat in front of a table on which a keyboard and a computer monitor were positioned. They were monitored by a video camera. In order to attain an optimal, non-tiring hand position and a similar way of key pressing over subjects (i.e. while only moving the wrist, hand, and index finger) a wooden armrest was used by the subjects of 4.6 cm height, 9.6 cm wide, and 35 cm length which was lifted about 2 cm at the side of the keyboard.

3 RESULTS

The influence of spuriously long response times was removed by excluding trials in which T_1 exceeded 700 ms in the one and three-key conditions or 900 ms in the five-key condition, or interresponse times T_2 through T_5 exceeded 300 ms. These cutoff values were chosen fairly conservatively and were derived from a T plus 3 standard deviations criterion in the first two sessions. In total less than 2 percent of all trials were removed by this procedure. Analyses of variance (ANOVAs) were performed on average times and arcsine transformed error percentages per session.

3.1 One-key condition

An analysis of errors did not yield significant effects. Mean error percentage was 1.8%.

3.1.1 *Compatibility effects*

The average compatibility effect in all four one-key sessions amounted to 44 ms [compatible 348 ms, incompatible 392 ms, $F(1,20)=187.5$, $p<0.001$]. The compatibility effect emerged in depression times (33 ms) as well as in movement times (11 ms) [T_{p1}: 261 and 294 ms, $F(1,20)=120$, $p<0.001$); T_{m1}: 87 and 98 ms, $F(1,20)=49.2$, $p<0.001$)]. The compatibility effect tended to decrease, from 52 ms in the first one-key session to 45 ms, 40 ms, and 40 ms in the later one-key sessions [see Fig. 2, $F(3,60)=2.4$, $p<0.08$]. Further analyses showed that this reduction concerned key depression and not movement: the compatibility effect in T_{p1} decreased from 41 ms in the first one-key session to 28 ms in the last two one-key sessions [$F(3,60)=3.8$, $p<0.05$] whereas the compatibility effect in T_{m1} remained at a level of about 11 ms [$F(3,60)=0.2$].

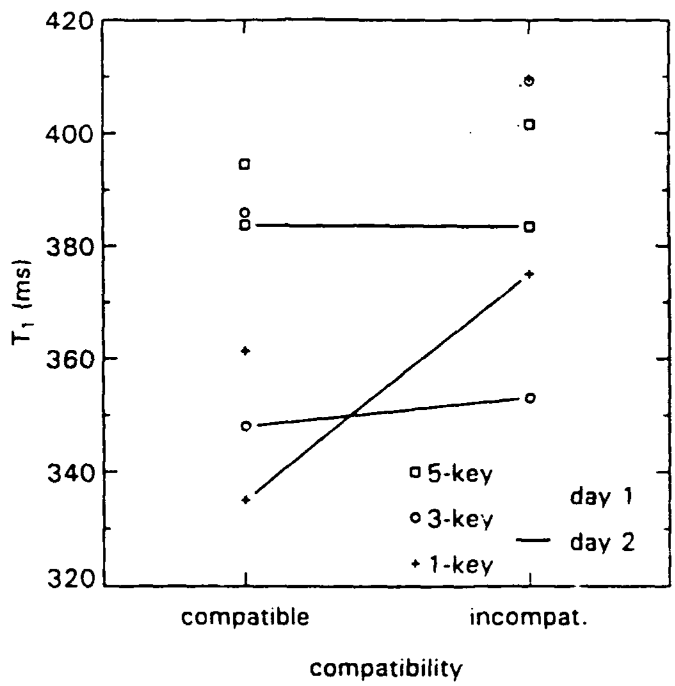

Fig. 2 Sequence initiation time as a function of compatibility, sequence length, and day.

3.1.2 *Remaining effects*

T_1 decreased with practice in subsequent one-key sessions: from 395 ms in the first one-key session to 376 ms, 353 ms and 357 ms, respectively, in the later sessions [$F(3,60)=24.9$, $p<0.001$]. This general effect of practice also emerged in depression and movement times: T_{p1} amounted to 295, 283, 264, 269 ms in subsequent one-key sessions [$F(3,60)=18.2$, $p<0.001$] and T_{m1} was 100, 93, 89, 88 ms in these sessions [$F(3,60)=10.2$, $p<0.001$]. No differences were found between three- and five-key subjects.

3.2 Three- and five-key conditions

Again, error analysis showed no significant effects. Mean error percentage amounted to 3.6%.

3.2.1 *Compatibility effects on* T_1

Pooled over sessions, there was a compatibility effect on T_1 in the multi-key conditions of 8 ms [385 and 377 ms, respectively, $F(1,20)=5.1$, $p<0.05$]. In the one- vs. multi-key condition × sequence length × compatibility × session ANOVA, the compatibility effect was found to be smaller in the multi-key than in the one-key condition [$F(1,20)=67.0$, $p<0.001$).

Subsequent analyses showed that the compatibility effect was caused by depression and not by movement time: the compatibility effect amounted to 8 ms in depression time [T_{p1}: 263 vs 271, $F(1,20)=5.6$, $p<0.05$] and was absent in movement time [$F(1,20)=0.3$]. The 2 × 2 × 2 × 4 ANOVA confirmed that the compatibility effect in depression times as well as in movement times was significantly larger in one-key than in multi-key sequences [33 vs. 8 ms, $F(1,20)=38.3$, $p<0.001$; 11 vs. 0 ms $F(1,20)=16.6$, $p<0.001$, respectively].

As depicted in Fig. 2, the compatibility effect on T_1 in the three-key condition at day 1 (409-386=23 ms) was larger than in that condition at day 2 (average compatibility effect was 353-348=5 ms) and larger than in the five-key condition at day 1 and 2 (average compatibility effect resp. 402-395=7 and 384-384=0 ms) but this was not supported by a significant length × compatibility × session interaction [$F(10,200)=0.6$] in the T_1-analysis. Close examination of the data suggest that this interaction did not reach significance because T_1 in the five-key condition was quite noisy in the day 1 sessions. Yet, a marginally significant length × session × compatibility interaction [$F(10,200)=1.8$, $p<0.07$] was found in the T_{p1} analysis indicating that in the three-key condition the average compatibility effect of 22 ms on day 1 (22, 17, 31, 27, and 11 at subsequent day 1 sessions) reduced remarkably to about 3 ms on day 2 (4, 3, 2, 6, 0, 2 ms at subsequent day 2 sessions). In contrast, the compatibility effect in T_{p1} of the five-key condition did not change at all with practice (averages at day 1 and 2 were both 4 ms). Separate analyses on T_1, T_{p1}, and T_{m1} obtained in the five-key condition at day 2 did not reveal any significant effects of compatibility. Table I reviews the compatibility and practice effects found in the various conditions and shows levels of significance obtained by planned comparisons (not discussed in the text).

Table I Effects of compatibility and practice on pressing, movement and total interkey times (in ms). Compatibility effects at day 2 are shown between parentheses. Levels of significance as found in planned comparisons are also indicated: - stands for non-significance, * for p<0.05, ** for p<0.01, and *** for p<0.001.

			T_1		T_2		T_3		T_4		T_5	
one-key	compat.	p[1]	33^{***}	(29^{***})								
		m	11^{***}	(11^{***})								
		m+p	44^{***}	(40^{***})								
	practice[2]	p	-26^{***}									
		m	-12^{***}									
		m+p	-38^{***}									
three-key	compat.	p	11^{*}	(3^{-})	1^{-}	(4^{*})	2^{*}	(3^{-})				
		m	2^{-}	(2^{-})	0^{-}	(1^{-})	2^{-}	(0^{-})				
		m+p	13^{*}	(5^{-})	1^{-}	(4^{-})	4^{**}	(3^{-})				
	practice[3]	p	-59^{***}		-2^{-}		-15^{*}					
		m	-13^{-}		-6^{-}		-9^{***}					
		m+p	-72^{***}		-8^{-}		-24^{***}					
five-key	compat.	p	4^{-}	(4^{-})	1^{-}	(0^{-})	1^{-}	(3^{-})	3^{-}	(4^{-})	2^{-}	(2^{-})
		m	-2^{-}	(-3^{-})	-1^{-}	(-3^{-})	-1^{-}	(-2^{-})	1^{-}	(1^{-})	0^{-}	(-1^{-})
		m+p	3^{-}	(0^{-})	-1^{-}	(-2^{-})	0^{-}	(1^{-})	4^{-}	(5^{-})	1^{-}	(1^{-})
	practice[3]	p	-20^{-}		-1^{-}		-6^{-}		-4^{-}		-10^{*}	
		m	$+7^{-}$		$+5^{-}$		-8^{***}		0^{-}		-12^{**}	
		m+p	-13^{-}		$+5^{-}$		-14^{**}		-4^{-}		-22^{***}	

1 m: movement time, p: pressing time, p+m: total (interkey) time;

2 obtained by subtracting times obtained in the last one-key session from those obtained in the first one-key session;

3 obtained by subtracting times obtained in the last two multi-key sessions from those obtained in the first two multi-key sessions.

3.2.2 *Compatibility effects on* T_2 *to* T_5

Separate ANOVAs on interkey intervals T_2 to T_5 (T_2 and T_3 ANOVAs included sequence length as factor - T_4 and T_5 ANOVAs did not) showed no significant compatibility effects on T_2, T_4, and T_5. Only on T_3 a compatibility × length interaction was encountered indicating a minor compatibility effect in three-key T_3s (4 ms) but not in five-key T_3s [0 ms, $F(1,20)=4.7$, $p<0.05$].

One significant compatibility main effect was encountered in the ANOVAs of depression and movement times: T_{p3} in the compatible condition was 2 ms shorter than in incompatible condition [$F(1,20)=6.2$, $p<0.05$]. This was not different for three- and five-key conditions [both 2 ms, $F(1,20)=0.5$]. A trend

toward a compatibility × length × session interaction on T_{p3} [$F(10,200) = 1.8$, $p < 0.07$] was also found. This was caused by a relatively large compatibility effect in the first session of the three-key condition (9 ms) as compared to the other sessions in the three- and five-key conditions: the average size of the compatibility effect in the other three-key sessions was 1 ms and in all five-key sessions 2 ms. The effect was marginally significant in a planned comparison of session 1 vs. all other sessions, the compatible vs. the incompatible condition, and the three- vs. the five-key condition [$F(1,20) = 3.7$, $p < 0.07$].

The only effect of compatibility that was found in analyses of day 2 data was a main effect of compatibility on T_{p3} [3 ms, $F(1,20) = 4.8$, $p < 0.05$]. The average size of this effect was equal in three- and five-key conditions.

3.2.3 *Remaining effects on* T_1

In the first session, T_1 in the five-key condition was equal to T_1 in the three-key condition (both 429 ms) which effect could be attributed to the earlier mentioned slow T_1 in the incompatible condition. With practice, T_1 in the three-key condition decreased faster and more than T_1 in the five-key condition ending up with T_1s of 391 ms and 347 ms in the last two sessions. This resulted in the sequence length × session interaction [$F(10,200) = 3.3$, $p < 0.001$] as mentioned earlier. Movement time (T_{m1}) decreased faster with practice in the three- than in the five-key condition [$F(10,200) = 1.8$, $p < 0.06$] but the main effect of practice on T_{m1} was not significant [$F(10,200) = 1.1$, $p > 0.20$]. The T_{p1}-analysis showed a larger decrement in the three-key condition with practice than in the five-key condition [$F(10,200) = 2.7$, $p < 0.01$]. In the three-key condition T_{p1} dropped from 306 ms in session 1 and 2 to 247 ms in the last two sessions, in the five-key condition it dropped from 282 ms to 263 ms.

3.2.4 *Remaining effects on* T_2 *to* T_5

Several main effects of session were found: T_3, T_4, and T_5 all decreased with practice [average values in first and last two sessions were 180 and 161 ms, $F(10,200) = 11.6$, $p < 0.001$; 186 and 182 ms, $F(10,100) = 2.3$, $p < 0.05$; and 184 and 162 ms, $F(10,100) = 6.9$, $p < 0.001$]. There were trends that T_3 was smaller in the three- than in the five-key sequence [160 and 175 ms resp., $F(1,20) = 3.3$, $p < 0.09$] and that T_3 reduced more with practice in the three-key condition than in the five-key condition [three-key: from 176 to 152, five-key: from 184 to 170 ms $F(10,200) = 1.7$, $p < 0.09$]. All practice effects were due to depression as well as movement times. Analyses of depression times showed practice effects on T_{p3}, T_{p4}, and T_{p5} [10 ms, $F(1,20) = 6.2$, $p < 0.05$; 3 ms, $F(10,100) = 2.3$, $p < 0.05$; and 10 ms, $F(10,100) = 3.6$, $p < 0.001$, resp.]. Movement time analyses revealed practice effects on T_{m3} and T_{m5} [9 ms, $F(10,200) = 6.0$, $p < 0.001$; 12 ms, $F(10,100) = 2.3$, $p < 0.05$, resp.].

The analysis of T_2 yielded a length × session interaction [$F(10,200)=3.0$, $p<0.01$] which was caused by a T_2 decrement in the three-key condition of 8 ms (session 1 & 2: 188 ms vs. session 14 & 15: 180 ms) and a T_2 increment of 5 ms in the five-key condition (198 and 203 ms). A length × session interaction on T_{m2} [$F(10,200)=3.0$, $p<0.01$] indicated a decrease with practice in the three-key condition of 6 ms and an increase in the five-key condition of 5 ms. The only main effect of sequence length was encountered on T_{m3} were the time to move to the next key was 13 ms faster for a three-key condition than for a five-key condition [$F(1,20)=5.1$, $p<0.05$].

Multivariate planned comparisons were carried out to find whether the decrease with practice (first two vs. last two sessions) was different for the various interkey intervals. In the three-key condition T_3 decreased more than T_2 [$F(1,20)=20.8$, $p<0.001$; see Table I]. In the five-key condition, T_2, which increased with practice, was different from the decreasing T_3 and T_5 [resp. $F(1,20)=29.6$, $p<0.001$; $F(1,20)=20.1$, $p<0.001$] and marginally different from the slightly reducing T_4 [$F(1,20)=3.0$, $p<0.10$]. The decrease of T_3 exceeded the T_4 decrement [$F(1,20)=5.2$, $p<0.05$] but not the T_5 decrement [$F(1,20)=2.3$, $p>0.10$]. Finally, T_4 reduced less with practice than T_5 [$F(1,20)=42.6$, $p<0.001$].

3.3 Summary of the results

An overview of the effects of compatibility and practice is provided in Table I. There was a clear compatibility effect in the one-key condition which was apparent in both depression and movement times. The compatibility effect was also found in the time to initiate three- and five-key sequences but it was much smaller than in the one-key condition. Planned comparisons as presented in Table I showed that the compatibility effect in the three-key condition disappeared with practice while in the five-key sequence it was virtually absent right from the beginning. This yielded a marginally significant interaction on T_{p1} but no interaction was found on T_1. In the multi-key sequences the compatibility effect was due only to pressing and not to movement time. Besides, compatibility effects were found at T_3 and T_{p3} at three-key conditions. Part of the compatibility effect on T_{p3} disappeared after session 1 so that at day 2 a minor effect on T_{p3} remained. This effect was equally large in the three- as in the five-key condition.

After two sessions, the time for initiating five-key sequences became longer than the time for initiating three-key sequences. This effect was caused by a shorter depression time of the home-key. Interkey times generally decreased with practice. Multivariate testing showed that this effect was stronger for T_3 and T_5 than for the three-key-T_2 and T_4. In the five-key condition T_2 increased with practice which could entirely be attributed to an increasing T_{m2}. The practice effect on T_3 and T_5 was due to both a shorter depression and movement time, on the three-key-T_2 it was due to a shorter movement time, and on T_4 it was

solely due to a shorter depression time. Besides, T_{m3} was slower in the five- than in the three-key condition, irrespective of practice.

4 DISCUSSION

The primary purpose of this experiment was to study whether response selection can concur with execution of a sequence of prior movements and to what extent movement execution is hampered by concurrent response selection. This was investigated in an experiment in which subjects practiced key pressing sequences, the last key of which was indicated by the stimulus while the earlier key presses were fixed. In order to trace the moment of response selection the mapping between stimulus and key was spatially compatible in one block of trials and incompatible in the other block.

The results are quite straightforward: the additional time on T_1 required to select an incompatible stimulus-dependent key - 44 ms in the one-key condition - disappeared almost entirely in the presence of a fixed sequence of preceding key presses. Planned comparisons showed that the reduction of the compatibility effect with practice on T_1 was significant in the three-key sequence and not in the five-key sequence but this was not substantiated by a significant interaction. Close examination of the data suggested that this interaction did not reach significance because T_1 in the five-key condition was quite noisy in the day 1 sessions which may indicate that concurrent response selection was not always easy to use early in practice. In the three-key sessions on day 1, the time to release the home-key (T_{p1}) still exhibited a compatibility effect of 22 ms but at day 2 this effect reduced to mere 3 ms. This yielded a marginally significant interaction. In addition, the time of depressing the second key (T_{p3}) showed a compatibility effect of 9 ms in the first session of the three-key condition which also virtually disappeared in later sessions. This suggests that in early practice the final stimulus-dependent key of the three-key condition was selected before sequence initiation while response selection became concurrent at later stages of practice. In contrast, the five-key condition suggests that there was virtually no compatibility effect right from the start of the experiment and that no practice was required for concurrent response selection.

Together, these results show that, after practice, response selection concurred with executing earlier key presses with virtually no interference. With additional practice no interference will probably remain at all. It appears that, to attain fully concurrent selection of responses, more practice is required as the sequence is shorter. If not only selection of single responses but also of chunks (including several movements) can be selected concurrently, then the mechanism of concurrent selection and execution may indeed be responsible for the possibility to produce long sequences in a flexible manner without evident pauses (e.g. Salthouse, 1986; Shaffer, 1976).

The earlier result that, irrespective of practice, the time to initiate a fixed sequence remained longer than the time to initiate a sequence with a final stimulus-dependent response (Verwey, in press), appears not to have been caused by a lack of concurrent response selection. Instead, concurrent selection of the stimulus-dependent response may have well developed early in practice and, as indicated in the introduction, the extra time required for initiating the sequence with the stimulus-dependent key may have been required for stimulus identification which was not required for the fixed sequences. Note that this is consistent with evidence that, if the system is set to identify stimuli, no actions are carried out until full stimulus identification has been achieved (Sanders & Houtmans, 1985; Sanders & Rath, 1991).

One wonders about how practice made response selection increasingly concurrent in the three-key condition. In fact, practice speeded up sequence production so that actually less time remained available for response selection. Moreover, as also confirmed in the present data, practice has only a minor effect on the time needed for selecting an incompatible response (Fitts & Seeger, 1953; Dutta & Proctor, 1992). Why, then, would practice contribute to concurrency of response selection? In principle there are two possibilities. Either sequence execution required less attention with practice or timesharing became more efficient and released attentional resources. This distinction is related to Brown and Carr's (1989) intratask automaticity and task combination strategies. Perhaps processes required for sequence execution were faster with practice but speed limitations due to mechanical constraints prevented a continuing increase of execution speed beyond some level of performance (see e.g. Gentner, 1987). This may have resulted in an increasing amount of free attention or, in other words, as a reduction of attentional demands (e.g. Holding, 1989; Schmidt, 1988). Subsequently, the attention freed by practice may have allowed concurrent response selection. Note that an important consequence of this reasoning is that a multiple resource view is not necessary to explain concurrent response selection: concurrency would not be possible because different resources are tapped but because processing time is freed by mechanical slowness. Without mechanical slowness concurrent response selection may not be possible. This may happen when a multi-finger key pressing sequence is produced (cf. Inhoff et al., 1984).

Alternatively, subjects may have learned the temporal dynamics of how to divide attention between key pressing and response selection and, hence, to efficiently combine execution and selection. One way to test the merits of these alternatives is to have subjects thoroughly practice short fixed sequences followed by conditions in which concurrent response selection is required. According to the notion that an increasing amount of attention is freed with practice no additional practice is needed when suddenly concurrent response selection is required; according to the notion of strategic task combination practice in concurrent response selection is required anyway.

Besides the issue of concurrent response selection the data also show two well-known phenomena that are frequently observed in research on sequence production. The first phenomenon concerns the complexity effect, i.e. that the time needed to initiate a longer sequence is usually longer than the time to initiate a shorter sequence (e.g. Henry & Rogers, 1960; Verwey, 1992). Compatible one-key responses were initiated faster than compatible three-key sequences which, in turn, were initiated faster than compatible five-key sequences. It is interesting to see that this also occurred for incompatible three- and five-key sequences. Hence, the increased demands of selecting incompatible responses hardly affected the complexity effect in the multi-key sequences which only adds to the notion that selection of the last response occurred after sequence initiation. The present data also demonstrate that with only limited amounts of practice the complexity effect may not appear because concurrent processing is possible with long but not with short sequences.

Second, in the three-key condition, T_3 decreased more with practice than T_2, replicating an earlier finding (Verwey, in press). Because in Verwey (in press) this effect was independent of whether or not the last key was stimulus-dependent, the conclusion was drawn that with increasing practice motoric unpacking of the third key press shifts in time so as to occur during or even before the second key press. The present results show something similar to occur in the five-key sequence. Yet, in the five-key sequence groups of key presses appear to evolve: two interkey intervals hardly reduced with practice (T_2 even increased by 5 ms and T_4 reduced only 4 ms) and two others decreased considerably (T_3: 14 ms and T_5: 22 ms). This suggests that, with practice, an increasing amount of processing occurred during T_2 and T_4 which allowed T_3 and T_5 to decrease more with practice. In other words, the key pressing sequence was increasingly executed as two two-key segments. This reminds of notions that memory codes in a motor program form a hierarchical structure in that some sequence elements are linked more closely than others. This has been conceptualized as a tree-traversal process, working top-down and left-right through a hierarchical structure of the program (Povel & Collard, 1982; Rosenbaum, 1985; Rosenbaum et al., 1983).

The observation that concurrent response selection occurred in the presence of concurrent unpacking suggests that response selection and unpacking are independent processes and that in the event of one the other need not be hampered. The new element in the present results is that practice may play a role in the development of grouping while in earlier reports grouping was found to occur without practice (e.g. Rosenbaum, 1985). An interesting question, then, is whether the reduction of attentional demands with practice, especially suggested by the gradual development of concurrent response selection in the three-key sequence, is related to response grouping (i.e. chunking). That is, grouping may be used to concentrate attentional needs of sequence execution at some moments thereby freeing attention at other moments.

A last point for discussion concerns the distinction between depression and movement times. The rationale was that rapid movements, as used in the present study, may be ballistic and therefore not subject to interference by concurrent processing whereas key depression probably indicates cognitive processes (e.g. unpacking a motor program from a motor buffer - Sternberg et al., 1978; Van Galen et al., 1986) and would therefore be more sensitive to capacity limitations incurred by concurrent processing. Consistent with this view an effect of compatibility in multi-key conditions emerged on depression time and not on movement time. Yet, these effects were quite small. More importantly, in the one-key condition movement time was affected by compatibility which, in retrospect, has been reported before (Simon, 1968). Again, the key press grouping effect emerged in depression as well as in movement time which contradicts the notion that cognitive processes only slow down key depression. At a theoretical level these observations suggest that the movements in the sequence were not fully ballistic. This corresponds to the finding of lasting interference between key pressing and a secondary task (Verwey, in press) and suggests that pressing keys with one finger is and remains attention demanding with practice. This notion corresponds to findings with other rapid movement tasks like writing and aiming (e.g. Bootsma & Van Wieringen, 1990; Van Doorn & Keuss, 1992; Proteau et al., 1992; Young & Zelaznik, 1992). At a methodological level, it appears that the distinction between depression and movement time does not make an unambiguous differentiation between levels of task interference and that future research should use the interval between on- or offset of subsequent key presses to investigate the production of key pressing sequences.

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This paper addresses the issue of selecting a response while executing earlier response movements. Although there is the general notion that this may be possible there is no conclusive evidence on whether it can occur without interference. A direct test of whether concurrent response selection of a present and execution of previous responses develops with practice was carried out by having subjects press a number of keys, determined in advance, prior to pressing a stimulus-dependent key. Response selection demands were varied by utilizing spatially compatible and incompatible stimulus-response mappings the demands of which are known not to diminish much with practice. The results show that the longer time needed to select an incompatible response vanishes almost entirely when the stimulus-dependent response is preceded by two or four predetermined key presses. The conclusion is drawn that response selection can concur with the execution of movement sequences without interference.

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